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Profiling the integrated application of multiple representations for the teaching of chemical concepts: teaching practices based on multiple representations

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Abstract
Multiple representations (MRs) have attracted much attention in the field of science education. When effectively integrated into teaching, they enable students to construct meaning from chemical phenomena and foster deeper conceptual understanding. However, existing studies have highlighted the difficulties teachers face in selecting and combining MRs to support students' learning of chemical concepts. To address this issue, this study analyzes 38 high-quality chemistry concept teaching cases (HQTC) covering key concepts at both junior and senior levels. Three mainstream frameworks of MRs in science education (Johnstone's, Gilbert's, and Ainsworth's) were applied to conduct multidimensional coding of MRs in these cases, which were then examined using descriptive statistics, correlation analysis, and hierarchical cluster analysis. The findings indicate that HQTC exhibit the following features in their use of MRs: (1) with respect to representational level, it shows an emphasis on the organic integration of macroscopic, submicroscopic, and symbolic representations; (2) with respect to representational function, there is a focus on representations with complement and construct functions; (3) with respect to representational form, it shows a prevalence of static visual and chemical symbols, with representations overall characterized by richness and diversity. Moreover, the use of MRs varied systematically across different teaching stages, aligning with students' cognitive needs as they progressed from preparation and initial construction to understanding, consolidation, summarization, and application. Based on these results, the study proposes practical suggestions for the design and application of MRs, with the aim of providing actionable guidance for concept teaching practices and offering an analytical framework for evaluating chemistry teaching cases.

Keywords Multiple representations, Conceptual understanding, Secondary education, Concept teaching, Chemistry education

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Introduction

Concept teaching has received considerable attention in the field of chemistry education, and many researchers have examined how to effectively promote students' understanding of chemical concepts (Sweeder et al., 2019; Jegstad, 2024; Kiernan et al., 2024). Conceptual understanding is achieved by noticing or discerning features in representations and reasoning about them in meaningful ways, which involves attending to, reflecting on, and constructing connections (Eriksson et al., 2014; Rau, 2016). Teachers need to provide representational scaffolds to help learners acquire and deepen conceptual knowledge (Airey & Linder, 2009; Ryan & Stieff, 2019).

"Representation" is a psychological term that reflects and describes external artifacts that help individuals make sense of the world (Taber, 2013). In teaching, external representations are artifacts placed in the public domain by teachers to symbolize a concept or idea, with the aim of enabling students to construct their own internal representations, or mental models (Gilbert, 2005; Kim et al., 2019). While different external representations may convey similar information, they support learning in different ways and afford distinct advantages. As such, how to effectively integrate multiple representations (MRs) to support students' conceptual understanding has become a central theme in chemistry education research (Madden et al., 2011; Sanchez, 2025).

This study aims to explore how MRs can be integrated into secondary school chemistry concept teaching to help teachers design MR-based instruction and enhance students' conceptual understanding. High-quality chemistry concept teaching cases (HQTC), which have been reviewed by experts, were selected as the study object. These cases represent a high level of MRs integration in practice. By analyzing these cases, the study seeks to extract effective teaching strategies, providing practical guidance for the integration of MRs in secondary chemistry education.

Literature review

Previous research has demonstrated that MR-based instruction provides significant benefits for students' learning of chemistry. First, it helps students establish more stable connections between concepts and reduce misconceptions (Pierson et al., 2022; Lichtenberger et al., 2024); second, it enables the visualization of submicro processes and facilitates connections between macroscopic and submicro levels (Derman & Ebenezer, 2018; Kim & Paik, 2019); third, it stimulates students' interest in explaining and exploring scientific phenomena (Ye et al., 2019; Chen et al., 2023). With the development of information technology, the widespread availability of multimedia and interactive tools in classrooms has further expanded teachers' opportunities to design MRs (Taber, 2018; Hammer & Avram, 2024). The selection and combination of these MRs significantly impact students' conceptual learning outcomes (Hand & Choi, 2010; Taber, 2013; Permatasari et al., 2022). Appropriately designed MRs with suitable forms and quantities can effectively facilitate learning, whereas excessive, irrelevant, or redundant MRs may distract students, increase extraneous cognitive load, trigger erroneous conceptual mappings, or even induce acute stress responses, ultimately undermining the effectiveness of concept teaching (Minkley et al., 2018; Zuhri et al., 2023). The aforementioned research emphasizes both the benefits and challenges of using MRs in chemistry education. It aligns with the aim of this study to explore how MRs are integrated across different teaching stages, particularly in secondary school chemistry teaching.

Dual coding theory, Mayer's multimedia learning hypotheses, and cognitive load theory provide a solid foundation for explaining the role of MRs in chemistry learning (Wu & Puntambekar, 2012). Dual coding theory posits that humans have two distinct but related cognitive systems: one for processing verbal information (the verbal response system) and another for processing nonverbal information (the mental representation system). Learning outcomes are significantly enhanced when learners can engage both systems simultaneously and integrate them (Paivio, 1990). Building on this theory, Mayer (2002) elucidated the cognitive processes involved in multimedia learning. His assumptions of dual channels, limited working memory capacity, and active processing further clarify how the combination and presentation of MRs influence cognitive processing (Robinson, 2004). This interpretation also aligns with cognitive load theory, underscoring that MRs design must balance the amount of information with students' cognitive processing capacity (Sweller, 1994). The aforementioned research highlights the importance of understanding cognitive mechanisms in MR-based instruction, which is crucial for designing effective chemistry teaching strategies.

Existing research has clearly articulated the benefits of MRs in chemistry education and explored how they facilitate students' conceptual learning. In concept teaching, effectively integrating MRs is crucial for supporting students' comprehension of chemical concepts. Ferreira and Lawrie (2019) integrated Johnstone, Gilbert, and Ainsworth's frameworks to analyze the integration of MRs in university chemistry courses using slide resources, proposing an effective analytical framework. However, this research primarily focused on the integration of MRs in slide resources, overlooking other MRs in the classroom. Additionally, due to differences in students' cognitive levels across educational stages, the conclusions drawn may be difficult to generalize to secondary school chemistry education.

Existing research suggests that students' information processing goals and needs vary significantly across different teaching stages, and teachers should provide differentiated MRs based on students' cognitive development and task requirements (Chang, 2018; Hahn & Klein, 2022). This indicates that the design of MRs should be adjusted according to the specific teaching stages. However, there is limited research exploring the integration and application of MRs across different teaching stages.

In summary, existing research has paid limited attention to the integration of MRs in secondary school chemistry teaching. Furthermore, there is a lack of detailed analysis on how MRs are integrated and applied across different teaching stages. Therefore, this study aims to fill this gap by systematically analyzing how MRs should be integrated in secondary school chemistry education, particularly in different teaching stages.

Theoretical framework

Exploring how teachers select and combine MRs in concept teaching requires a multidimensional perspective (Ferreira & Lawrie, 2019). In the field of science education, three mainstream frameworks of MRs are commonly used:

1. Alex Johnstone's triplet representation framework: Johnstone (1982) divided chemistry knowledge into three domains—macroscopic, submicro, and symbolic—and emphasized that understanding chemical concepts requires establishing internal connections among these three levels of representation. This triplet framework is widely regarded as a key manifestation of conceptual understanding in chemistry (Yaman, 2020).
2. John Gilbert's representation form framework: Gilbert (2005) categorized external representations into five types: concrete (or material), chemical symbols, visual, gestural, and verbal. External representations are an important support for learning and understanding concepts. Researchers have paid particular attention to the first four categories for their role in concept teaching (Zhang & Linn, 2011), and these categories have often been extended into research on visualization in science education. Verbal representations are usually used as explanations of other visual representations and are often analyzed separately (Adadan, 2013; Cabello et al., 2019).
3. Shaaron Ainsworth's representation function framework: Ainsworth (1999) proposed that when MRs are combined, they serve three main functions: to complement, constrain, and construct. Analyzing the function of MRs in concept teaching is important for us to explore how to organize representations to support conceptual understanding (Goldman, 2003; Baptista et al., 2019).

Together, these three frameworks approach MRs from the perspectives of level, form, and function, respectively, thereby revealing different mechanisms through which MRs support students' conceptual understanding. The choice of level, form, and function as analytical dimensions highlights their distinct roles in supporting conceptual learning: level addresses cognitive processes, form examines presentation methods, and function examines how representations complement, constrain, or construct knowledge. Since the process of concept construction is usually closely tied to specific teaching stages, this study integrates all three frameworks to provide a more comprehensive analysis of how MRs are selected and combined across different stages of concept teaching in order to support students' conceptual understanding (Lawrie, 2021a).

Research questions

This study analyzed the use of MRs in a set of HQTC to identify the patterns and characteristics of how expert teachers integrate MRs in concept teaching, providing a valuable reference for both education researchers and frontline teachers. Specifically, the study addressed the following questions:

RQ1 What are the distributional characteristics of MRs in terms of level, form, and function in HQTC?

RQ2 What kinds of associations exist among the levels, forms, and functions of MRs used in HQTC?

RQ3 How do the integration patterns of MRs vary across different teaching stages in HQTC?

The contributions of this study are threefold: (1) it integrates Johnstone's, Gilbert's, and Ainsworth's frameworks to analyze HQTC, providing an analytical framework for evaluating MR integration in secondary chemistry teaching; (2) it explores the design features adopted by expert teachers in chemistry concept instruction and uncovers regularities in MR combinations across teaching stages; and (3) it provides actionable insights for both chemistry education researchers and practitioners, offering practical guidance for designing and organizing MRs in concept teaching.

Methods

Three independent MR frameworks were applied to code the HQTC and, in combination with concept teaching stages, to analyze the use of MRs in HQTC from the three dimensions of representational level, form, and function.

Data sources and sample selection

HQTC analyzed in this study were primarily drawn from the National Educational Resources Public Service Platform of the Ministry of Education of China. As these resources are publicly available, the data collection process was ethically compliant (Lawrie et al., 2021). These cases have reached a wide audience: the database has been accessed hundreds of thousands of times online and has provided design references for tens of thousands of secondary school chemistry teachers nationwide, thereby impacting a wide range of students.

The platform contains over 350 chemistry teaching cases. During the selection process, three criteria were applied: (1) the cases explicitly aimed to support students' understanding of chemical concepts; (2) at least three types of representation forms (excluding verbal representations) appeared in the teaching; and (3) the cases had won awards in national-level competitions. These criteria ensured that: (i) the cases represented concept teaching based on MRs, all vetted as high-quality instruction through expert review; and (ii) the representations included were deliberately and carefully designed, reflecting the collective expertise of chemistry teachers at the school or regional level, and thus worthy of analysis and documentation.

In the selection process, the first author initially screened all cases on the platform according to the three criteria, resulting in 84 candidate cases. The two authors then thoroughly discussed the use of MRs and the effectiveness of concept teaching in each case, ultimately selecting 38 HQTC. It is important to note that these cases underwent a rigorous review process and received high recognition from experts for both teaching content and methods. Therefore, selecting these HQTC as research objects ensures that the analyzed cases represent the best practices in current secondary school chemistry teaching, demonstrating how to effectively integrate MRs in chemistry concept teaching.

The 38 HQTC covered 20 core concept teaching topics. These core concepts are selected from the Next Generation Science Standards (NGSS) of the United States and the Chemistry Curriculum Standards of China. Five of the HQTC were selected from junior secondary chemistry cases, covering concepts such as "Chemical equations," "Law of conservation of matter," and "Energy's involvement in chemical changes." The remaining 33 HQTC were selected from senior secondary chemistry and broadly encompassed core concepts such as "Ionic bonding," "Equilibrium," "Atomic structure," and "Kinetics." Together, these cases covered the core concepts of secondary school chemistry, thereby meeting the relevant requirements of prior research (Lawrie, 2021b), and thus the sample size of this study was deemed appropriate.

For each HQTC, the available materials included a text version of the teaching design, a PowerPoint presentation (PPT), and a video recording of the classroom implementation. The text version of the teaching design provided detailed analysis of students' prior knowledge, while the video comprehensively documented teacher–student interactions and the representations employed. During the coding process, we cross-validated information across all three files for each case to generate a complete set of codes (see Appendix 1 for coding examples). Because HQTC were carefully crafted and repeatedly refined, no contradictions or inconsistencies were found across the different files for the same case during coding.

Ethical approval was not required for this study, as all teaching cases were publicly available through the National Educational Resources Public Service Platform.

Coding process

The coding of the teaching cases in this study consisted of two parts: coding of the teaching stages and coding of the representations used within each stage (see Appendix 1, Fig. S2 for the coding procedure; all coding was conducted using NVivo 12). After the initial coding was completed, two additional researchers were invited to independently code 19 randomly selected cases (approximately 50% of the total) for both teaching stages and representations, in order to establish inter-rater reliability. Both researchers held master's degrees in chemical education. Fleiss's kappa, a robust reliability statistic that accounts for chance agreement and allows for three or more raters (Wieselmann et al., 2020), was calculated. Agreement coefficients of 0.926 and 0.892 were obtained for the two parts of the coding, indicating high levels of reliability.

Teaching stages coding

Gagné (1968) argues that teaching consists of a set of events external to the student that are designed to support the internal process of learning. The eight basic events that must be completed in sequence in the learning process are attention, target anticipation, existing knowledge extraction, selective perception, semantic coding, response, feedback reinforcement, and extraction and application. Students need to process information differently in each of these events. Chen et al. (2004) divided the teaching events proposed by Gagné into three progressive teaching stages: the first three events are learning preparation, the next three are the completion of the learning tasks, and the last two are the transfer and generalization stages. Following Chen et al. (2004) classification of teaching stages and the basic process of concept formation, the structure of concept teaching was initially divided into three stages: concept–preparation, concept–formation, and concept–transfer. In the concept–preparation stage, students engage in preparatory activities, develop learning motivation, and set learning goals, which form the foundation for conceptual learning. The concept–formation stage focuses on the construction of concepts and constitutes the core of concept teaching. The concept–transfer stage involves summarization and application of concepts at the end of instruction, which is essential for deepening conceptual understanding.

After coding a small number of cases, we found that the preliminary classification was too broad and did not sufficiently capture the detailed processes through which students construct conceptual understanding. Therefore, the coding was refined based on specific learning activities within each stage: the concept–formation stage was subdivided into preliminary concept–construction, concept–understanding, and concept–solidification; and the concept–transfer stage was subdivided into concept–summarization and concept–application. The final classification thus comprised six categories: concept–preparation, preliminary concept–construction, concept–understanding, concept–solidification, concept–summarization, and concept–application. Details of the coding scheme are shown in Table 1.

Representation coding

Representation coding included the level, form, and function. The initial coding originated from the theories of Johnstone, Gilbert and Ainsworth. After coding a small number of cases, the researchers had many discussions to improve the coding method. The final coding and examples are presented (see Appendix 1, Tables S1 and S2).

(1) Representation level

The representation level included three categories: macroscopic, submicro and symbolic. Each representation was coded independently. If the same picture or PPT contained elements from multiple levels, the representation was divided according to the levels, and each resulting representation was coded and counted independently. Coding examples involving multiple levels are shown in Fig. S1 of Appendix 1.

(2) Representation form

Based on Gilbert's classification of external representation forms, this part of the coding process was partially adjusted.

First, because the verbal category is generally used as explanations for other representation forms in concept teaching (Adadan, 2013), and this form is usually discussed by researchers alone (Oliveira et al., 2015), the verbal representations of teachers and students are not discussed in this study. Second, to compare the differences between two visual representations, the visual categories were subdivided into dynamic and static visual forms. Finally, experiment is an important form of gestural representation in chemistry classes, and it is more important for the students to understand concepts than gestures, so the gestural category was revised to the experiment category. Therefore, the revised coding included five categories—chemical symbol, static visual, dynamic visual, experiment and concrete.

(3) Representation function

When coding the functions of representations, the researchers referred to the instructional designer's intended purpose to determine the function of each representation (Ainsworth, 1999). This approach ensured that the coding was closely aligned with the original instructional intent and facilitated subsequent statistical and hierarchical clustering analysis. In the same teaching cases, when information in one representation was complementary to information in the second representation, both were coded as the complement function. We defined the representations that appeared in earlier teaching stages, as well as the representations reflecting

Table 1 Teaching stage coding

Teaching stage		Teaching activities
Concept–preparation stage		Awaken existing knowledge and experience based on the situation, gain students' attention, define the learning tasks, and develop goal expectations.
Concept–formation stage	Preliminary concept–construction stage	Obtain specific information or perceptual knowledge related to concepts from practical life, experiments and other sources and form meaningful preliminary knowledge by linking existing knowledge and experience.
	Concept–understanding stage	Relate newly obtained specific information or perceptual knowledge to in-depth analysis in order to understand the underlying nature and principles of the phenomenon.
	Concept–solidification stage	Combine perceptual knowledge and rational analysis to establish internal correlation and form an overall understanding of the concept.
Concept–transfer stage	Concept–summarization stage	Extract and summarize the essential characteristics and general rules of concepts, sort concepts closely related to the learned concepts, form a stable conceptual network system, and expand the existing cognitive structure.
	Concept–application stage	Extract concepts and apply them to new situations, solve practical problems, and understand concepts.

students' prior knowledge described in the teaching design, as familiar representations; when such representations were used to clarify a concept or to prevent misconceptions, they were coded as the constrain function. When MRs created mental entities that supported new processes at a higher level of organization, they were coded as the construct–abstract function; When the students use the knowledge to explain the unfamiliar representation and the problem it involves, the representation was coded as the construct–extension function. Connecting MRs to analyze the internal associations between them was coded as the construct–relation function. The revised coding included five categories: complement, constrain, construct–abstract, construct–relation and construct–extension.

Statistical analyses

Statistical analyses were conducted to examine the characteristics of MRs used in HQTC and the possible relationships among them. First, descriptive statistics were used to report the frequencies of representational levels, forms, and functions. Next, Spearman's correlation coefficients were calculated to explore the strength of associations among the 13 independent coding categories of representations, with the aim of identifying potential combinatorial patterns in the application of MRs from different framework perspectives in concept teaching. Finally, hierarchical cluster analysis (HCA) was employed to investigate whether common features existed in the levels, forms, and functions of MRs across six types of teaching stages, in order to clarify how expert teachers design MRs in different stages of instruction. All analyses were conducted using SPSS 25.0.

HCA is a research method often used to explore the relationship between variables in chemistry education research (Linenberger & Holme, 2014; Lin et al., 2022). In this study, multiple data matrices were constructed in which each row represented a teaching stage of the same type (as the cases for cluster analysis) and each column represented the actual frequency of a coded representation (as the clustering variables). For the cluster analysis, the actual frequencies were standardized by converting them to Z scores (mean = 0, standard deviation = 1). In the SPSS agglomerative procedure, each teaching stages was initially treated as a separate cluster, which were then successively merged to form a hierarchical structure of nested groupings (Ye et al., 2015). The HCA results were visualized in a dendrogram (tree diagram), which depicts similarities or differences among groups in terms of inter-cluster distances, where longer branches indicate lower similarity and shorter branches indicate higher similarity. The dendrogram was generated using squared Euclidean distance and Ward's linkage method (Ward, 1963), which applies an agglomerative clustering criterion that minimizes the squared Euclidean distance between each teaching stages and its assigned cluster centroid (Rencher & Christensen, 2012).

Table 2 Actual code frequency in each category

Category		Frequency
Representation level	Macroscopic	439 (11.6)
	Submicro	100 (2.63)
	Symbolic	213 (5.61)
Representation form	Chemical symbols	202 (5.47)
	Static visual	388 (10.21)
	Dynamic visual	58 (1.53)
	Experiment	91 (2.39)
	Concrete	13 (0.34)
Representation function	Complement	337 (8.87)
	Constrain	85 (2.24)
	Construct	330 (8.68)
Construct function	Abstract	42 (1.11)
	Relation	170 (4.47)
	Extension	118 (3.11)

(Numbers in brackets are per-example averages)

Results

A total of 209 teaching stages and 752 representations were coded from the 38 HQTC, excluding the verbal or gestural behaviors of teachers and students during classroom interactions.

Descriptive statistical analysis

Descriptive statistics were used to present the overall distribution of representations in HQTC (see Table 2). Macroscopic representations were used most frequently (439 times, with an average of 11.6 per case), followed by symbolic representations (213 times, average 5.61), while submicro representations were used least often (100 times, average 2.63).

In terms of representational forms, static visual representations occurred most frequently (388 times, average 10.21), followed by chemical symbol forms (202 times, average 5.47). By contrast, dynamic visuals (58 times, average 1.53), experiments (91 times, average 2.39), and concrete forms (13 times, average 0.34) were relatively rare.

Regarding representational functions, complement (337 times, average 8.87) and construct (330 times, average 8.68) were the most frequently used, while constrain appeared less often (85 times, average 2.24). Within the construct function, relation (170 times, average 4.47) and extension (118 times, average 3.11) predominated, whereas abstract was used less frequently (42 times, average 1.11).

The results of the single-sample Kolmogorov–Smirnov test showed that, with the exception of the complement code, the distributions of all other codes were not

Table 3 Main features of representations used across six teaching stages

Teaching stage	Representation level	Representation form	Representation function
Concept–preparation stage	macroscopic	static visual	complement
Preliminary concept–construction stage	macroscopic	experiment or static visual	complement
Concept–understanding stage	submicro	static visual or dynamic visual	constrain
Concept–solidification stage	symbolic or macroscopic	chemical symbols or static visual	relation
Concept–summarization stage	macroscopic or symbolic	static visual or chemical symbols	abstract
Concept–application stage	macroscopic or symbolic	static visual or chemical symbols	extension

normally distributed ($p < 0.05$). Therefore, nonparametric methods were used in the subsequent analyses (Gordon et al., 2007).

Correlation analysis

Spearman's correlation analysis ($n = 752$ coded representations) was conducted to examine the relationships among representational levels, forms, and functions. The results indicated significant correlations across these three dimensions (see Appendix 4, Table S3). For example, the correlation coefficient between macroscopic representations and static visual forms was 0.50 ($p < 0.0005$), while the correlation between submicro representations and the constrain function reached 0.86 ($p < 0.0005$).

Hierarchical cluster analysis

HCA was applied to explore the characteristics of MRs use within the same type of teaching stage. The clustering results are presented in six dendrograms (Appendix 2, Fig. S3). In each dendrogram, the two largest clusters are labeled as Group A (larger number of cases) and Group B (smaller number of cases). In the following discussion section, analyses of the common features of MRs use within each type of teaching stage are based on the HCA results. Because Group B contained fewer than 15% of the cases in the concept–preparation, preliminary concept–construction, concept–understanding, and concept–solidification stages, only Group A was used for analysis in these categories to avoid bias (Chan & Bauer, 2014).

Mann–Whitney U tests were then conducted to determine whether significant differences existed between Group A and Group B in the concept–summarization and concept–application stages. Bonferroni corrections were applied to control Type I error (Gordon et al., 2007), and effect sizes were estimated using η^2 (small = 0.01, medium = 0.06, large = 0.14) (Richardson, 2011). The results, shown in Appendix 5 (Table S4), indicated that in the concept–summarization stage, Groups A and B differed significantly on several codes; likewise, in the concept–application stage, significant differences were also observed between Groups A and B across multiple codes. These findings provide the basis for the joint analysis of MRs use in the concept–summarization and concept–application stages.

Appendix 3, Fig. S4 presents the data for Groups A and B in bar chart form, while Table 3 summarizes the main features of representational levels, forms, and functions across the six types of teaching stages.

Discussion

The application of MRs in chemical concept teaching

The results from this study showed that each HQTC incorporated representations at the macroscopic, submicro, and symbolic levels, suggesting that the effective integration of these different levels of representation is essential for promoting conceptual understanding in chemistry. This finding is consistent with prior research (Johnstone, 1991; Talanquer, 2010), which also highlights the importance of integrating these representational levels for enhancing students' comprehension of chemical concepts. Further analysis revealed that macroscopic representations were used most frequently in HQTC—more than twice as often as symbolic representations and more than four times as often as submicro representations. This finding contrasts with the results of Ferreira and Lawrie (2019), who reported that symbolic representations were most common and macroscopic representations least common in university chemistry classrooms. Such differences suggest that the design and application of representational levels vary across educational stages. Since secondary school students' abstract thinking skills are not yet fully developed, they find it difficult to directly comprehend submicro and symbolic representations. At this stage, macroscopic representations not only serve as the prerequisite and foundation for understanding submicro representations (Berg et al., 2019) but also act as important carriers for advancing conceptual understanding. It is essential for students to engage with macroscopic representations in order to build perceptual experiences that serve as the basis for deeper cognitive processing. Therefore, in secondary school chemistry concept teaching, particular emphasis should be placed on the design and application of macroscopic representations.

With regard to representational forms, HQTC featured a large number of representations (an average of 19.8 per case) and diverse forms (at least three forms in each case). Among these, static visual and chemical symbols forms were used most frequently. Given that chemical symbols constitute the specialized language of chemistry (Chi et al., 2018), it is not surprising that chemical symbols representations were common in the cases. However, static visual representations were employed more than six times as often as dynamic visual ones. Although many studies have shown that, compared with static visuals, dynamic visuals can convey more information, better visualize submicro processes, and enhance students' cognitive engagement (Barak & Hussein-Farraj, 2012; Keiner & Graulich, 2020), they also carry a high information load. In HQTC, where numerous representations were already present, excessive use of dynamic visuals risked overloading students' cognition. These findings highlight that the choice of representational forms should provide students with the information necessary for concept construction while avoiding undue increases in cognitive load, which may otherwise lead to misconceptions (Minkley et al., 2018; Aminuddin et al., 2024).

The analysis of representational functions clarified the extent to which representation design supports conceptual understanding. Each HQTC included representations serving the complement, constrain, and construct functions, demonstrating that functionally diverse designs can positively support conceptual learning. HQTC particularly emphasized the complement and construct functions, reflecting the inherent roles of these categories: complement representations provide the foundation for students' basic understanding of concepts, while construct representations are essential for promoting deep understanding. Although constrain representations were less frequently used, they played an important role in helping students refine their comprehension of information provided by complement representations, thereby acting as an intermediate step that supports further conceptual construction (Baptista et al., 2019).

Relationships among MRs

The results of Spearman's correlation analysis indicated certain associations between the levels and forms of representations used in HQTC. For instance, the correlation coefficient between macroscopic representations and static visual forms was 0.50, while that between submicro representations and dynamic visual forms was 0.52. This suggests that when designing macroscopic representations, teachers often chose static visual forms, likely because static visuals provide sufficient information without imposing excessive cognitive load. By contrast, dynamic visual forms were frequently used to simulate submicro phenomena, offering students intuitive information that can facilitate their understanding of abstract chemical concepts (Berg et al., 2019).

We also observed strong associations between representational levels and functions in HQTC. For example, the correlation coefficient between submicro representations and the constrain function reached 0.86. This finding suggests that different levels of representations exhibit functional tendencies. In practice, therefore, representational level and function can be effectively combined when selecting and organizing representations. For example, teachers may design constrain representations to help students explain the microscopic principles underlying chemical phenomena.

The application of MRs in different teaching stages and their support for conceptual understanding

An important contribution of this study is its systematic analysis of the design and application of MRs across different stages of concept teaching. Overall, as instruction progresses, the levels, forms, and functions of representations exhibit distinct stage-specific characteristics (see Table 3 in the Results section). These findings provide practical reference points for chemistry teachers designing HQTC.

In the concept–preparation stage, the most common combination was macroscopic–static visual–complement. This combination effectively captures students' attention and enriches their prior knowledge through everyday contexts, thereby preparing them for subsequent concept construction (Taber, 2013).

In the preliminary concept–construction stage, the dominant combination was macroscopic–experiment/static visual–complement. Prior research has shown that learning complex chemical concepts depends on a rich base of perceptual knowledge (Derman & Ebenezer, 2018). Representations of this type help students acquire sufficient experiential knowledge, laying the groundwork for understanding submicro mechanisms.

In the concept–understanding stage, the most prominent combination was submicro–static/dynamic visual–constrain. Understanding the essential principles of concepts at the submicro level is necessary, but after building perceptual knowledge, students' comprehension often remains at a superficial level. Visualizing submicro processes through diagrams or animations helps students focus their thinking, construct deeper conceptual understanding, and eliminate potential misconceptions (Nakiboğlu & Nakiboğlu, 2019; Jere & Mpeta, 2024).

In the concept–solidification stage, both symbolic and macroscopic representations were used, with symbolic representations predominating; similarly, chemical symbol and static visual forms co-occurred, but chemical symbol forms were more frequent; the primary function was construct–relation. Symbolic representations, as highly abstract representations, act as intermediaries between macroscopic phenomena and submicro principles (Waight & Gillmeister, 2014). Thus, an important stage in constructing conceptual understanding is students' ability to comprehend symbolic representations and flexibly move between macroscopic and submicro perspectives via symbols.

In the concept–summarization stage, macroscopic and symbolic representations were used together, with macroscopic forms dominating; static visuals and chemical symbol forms coexisted, with static visuals more frequent; the primary function was construct–abstract. Since one of the goals of concept teaching is to help students achieve higher-level understanding and develop systematic knowledge structures (Venville & Dawson, 2010), teachers often used summarizing representations such as concept maps or mind maps to help students consolidate and generalize what they had learned.

In the concept–application stage, macroscopic and symbolic representations remained dominant, typically combining static visuals and chemical symbol forms; the primary function was construct–extension. At this stage, students were able to transfer and extend their conceptual knowledge to novel problem contexts, thereby deepening their mastery (Broman et al., 2018).

Taken together, these findings suggest that teachers should design and organize MRs with careful attention to the characteristics of each teaching stage. By drawing on the three MR frameworks, teachers can maximize the advantages of MRs in promoting conceptual understanding while avoiding inappropriate combinations or excessive use that might increase cognitive load and negatively affect learning outcomes (Nyachwaya & Gillaspie, 2016; Enero Upahi & Ramnarain, 2019).

At the practical level, different strategies can be applied in different stages. In the concept–preparation stage, teachers can build on students' prior knowledge by presenting pictures of familiar everyday contexts and posing the key question to be studied (Corradi et al., 2012).

In the preliminary concept–construction stage, teachers may use macroscopic experiments or relevant images to provide rich perceptual information, thereby supporting subsequent understanding of submicro principles (Treagust et al., 2003). In the concept–understanding stage, animations simulating submicro processes or models of particle structures can be used, with students guided to interpret and analyze the information in depth so as to construct accurate explanations (Won et al., 2014). In the concept–solidification stage, symbolic representations can help students connect macroscopic phenomena, submicro mechanisms, and symbolic expressions. For example, in the teaching segment on electrolytes (Appendix 6, Case 1), students linked dissolution phenomena, particle motion, and symbolic expressions while writing the ionization equation of sodium chloride. In the concept–summarization stage, teachers can guide students to use concept maps or mind maps to extract common attributes or rules from different phenomena, thus consolidating their understanding. For example, in the redox reactions segment (Appendix 6, Case 2), students constructed a concept map that captured the general features of the reaction type. In the concept–application stage, teachers can use pictures or symbolic representations of real-life contexts or problems, requiring students to engage in deeper cognitive processing and flexibly shift between representational levels. For instance, in the precipitation–dissolution equilibrium case (Appendix 6, Case 3), students applied their knowledge to propose practical solutions to a medical problem, demonstrating more advanced conceptual understanding.

Conclusions and limitations

This study demonstrates that the effectiveness of chemistry conceptual learning largely depends on how teachers select and combine external representations (Ryan & Stieff, 2019; Stieff, 2019). External representations provide the essential foundation for students to construct mental models. In well-designed concept teaching, teachers draw on the disciplinary characteristics of chemistry to select diverse forms of representation, which can stimulate students' interest and ensure the effective extraction of representational information (Davenport et al., 2018; Adadan, 2019). In this study, three multiple representation frameworks were applied to analyze 38 HQTC, with further analyses conducted across different teaching stages. The results showed that HQTC generally integrated macroscopic, submicro, and symbolic representations, but macroscopic representations predominated at the secondary level, reflecting students' developmental stage of cognition. In terms of form and function, teachers tended to use static visual and chemical symbol representations, with particular emphasis on complement and construct functions, thereby supporting students in developing deeper conceptual understanding. Moreover, the combinations of representations across different teaching stages exhibited stage-specific characteristics that aligned with students' cognitive needs as they progressed from preparation and construction to understanding, summarization, and application.

The contributions of this study are threefold. The theoretical contribution lies in combining Johnstone's, Gilbert's, and Ainsworth's frameworks to systematically reveal the relationships among representational levels, forms, and functions, providing an integrated perspective for understanding how MRs support conceptual learning. The methodological contribution lies in presenting a replicable research pathway that combines multi-source data, coding analysis, descriptive statistics, correlation analysis, and cluster analysis. The practical contribution lies in summarizing the patterns of representational combinations across teaching stages, thereby offering actionable guidance for teachers in designing representations for concept teaching.

Admittedly, this study has certain limitations. First, all selected cases were award-winning public cases, which precluded in-depth interviews with students to explore their processes of extracting and processing representational information, and did not allow for quantitative measures of students' conceptual understanding after instruction. Second, the data were limited to Chinese secondary school classrooms, leaving the cross-cultural applicability of the findings to be further examined. Third, while this study analyzed the application of representations in concept teaching from multiple perspectives, it did not involve the design and implementation of teaching interventions explicitly based on MRs.

Future research could proceed in several directions: (i) incorporating classroom observations, interviews, or other approaches to examine how students process and apply MRs in chemistry teaching; (ii) conducting experimental or quantitative studies to test the impact of different combinations of MRs on students' conceptual understanding of specific chemistry topics; (iii) undertaking cross-cultural comparisons to examine differences and commonalities in representational design across educational systems; (iv) leveraging emerging educational technologies to design and implement MR-based chemistry teaching, thereby extending the possibilities of representation design and testing the effectiveness of the instructional suggestions proposed in this study; and (v) investigating the professional development needs of chemistry teachers regarding MRs, with the aim of enhancing their understanding and application of MRs in the classroom.

Abbreviations

MRs	Multiple representations.
HQTC	High-quality chemistry concept teaching cases.

Supplementary information

The online version contains supplementary material available at https://doi.org/10.1186/s43031-025-00148-6.

Supplementary Material 1

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Author contributions

Yanxia Jiang conceived the study and designed the research. Ruilin Zhang collected and coded the data. Ruilin Zhang performed the statistical analyses. Ruilin Zhang drafted the manuscript. All authors read and approved the final manuscript.

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Data availability

The original teaching cases analyzed in this study are publicly accessible through the National Educational Resources Public Service Platform at https://portal-preview.ykt.eduyun.cn/. The coding manual, anonymized coding data, and analysis results are available from the corresponding author upon reasonable request. Representative coded examples are provided in Appendix 1 of this article.

Declarations

Competing interests

The authors declare that they have no competing interests.

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